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Industry 4.0: Latent Dirichlet Allocation and clustering based theme identification of bibliography

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ABSTRACT

Industry 4.0 with its fusion of technologies has brought an unprecedented growth in all sectors. In this paper, we first present the several pillars of Industry 4.0 which have contributed to the advancement of this field. Then, we perform a bibliometric profile of the Industry 4.0 publications in Web of Science by analyzing the publications and citation structure, most referenced publications, most productive and influential authors, organizations and countries. Further, an extensive analysis of the key words is presented along with the citation bursts of top keywords. Various visualizations tools have been to used show relationships between different bibliometric profiles. The individual growth of different research areas over the year is also presented. The results show promising growth of Industry 4.0 as a research area, various collaborative groups have been identified which are working extensively in the growth of the domain, spearheaded by China, however, considerable contribution of developing countries is also there. An abstract analysis is done using K-means clustering and Latent Dirichlet Allocation (LDA) to identify key research themes.

1. Introduction

The successive development of modern industry had been accounted for so many years, till the notion of Industry 4.0 was introduced in 2011 for the development of German economy (Lu, 2017). As we speak, we are in the fourth industrial revolution (popularly known as Industry 4.0). It envisages a new area of smart/digital/intelligent manufacturing. Industry 4.0 has drastically transformed the economic, political, social, and cultural landscape of the world. In simple interpretation, it is the data and knowledge integration among the technologies and encompasses the concepts of: cyber physical systems (CPS), Internet of Things (IoT), cloud computing, smart industries, big data and advanced analytics, extensive wireless networks, additive manufacturing (3D printing) (Zhou et al., 2015; Vaidya et al., 2018) etc. Industry 4.0 focuses on innovativeness, customization of products to individual and specific needs, decentralization, adaptability, and sustainability (Lasi et al., 2014). It basically intends to integrate the real/physical world with the virtual world.

More specifically, integration of Industry 4.0 should not only implement automation but also ensure higher operational proficiency and throughput. Considering the said effectiveness of Industry 4.0, many of the small and medium enterprises are transforming continuously into an Industry 4.0 ecosystem for better efficiency and improved processes. Moreover, many countries have now adapted the Industry 4.0 ecosystem for the obvious reasons and defined several pillars as per the requirements and need for that region. In this paper, we have tried to combine all those pillars, which covers the industrial and academics point-of-view. The combined pillars are represented pictorially in Fig. 1. Each pillar of Industry 4.0 holds a specific significance to that technological principle. These pillars are utilized in/by Industry 4.0 ecosystem as follows:

1. **Internet of Things (IoT's):** This signifies the accumulation of the objects and devices physically and virtually. Industry 4.0 basically utilizes the IoT's so as to execute the digital manufacturing. It is a dynamic concept that lies at the crossroads of computer, networking, and engineering technology (Wan et al., 2015). Although having a standard for communication between the two had been a challenge, over the years many industrial giants have formed some solutions.
2. **Big data:** For Industry 4.0, big data is exactly as the food to the human body. It keeps the performance enhanced by in-depth analytics. The machinery are generating huge chunk of data every moment through various sensors and thus it encourages industries to establish a wide and comprehensive look into their performance. The standard principles of big data are thus necessary for the Industry 4.0, which are: data as an industry, data as a tool and data as a strategy.
3. **System Integration:** There are two ways of system integrations in the whole Industry 4.0 ecosystem viz. Vertical integration (make the flexible modules to integrate within an industry for agility including logical layers such as: production, management,

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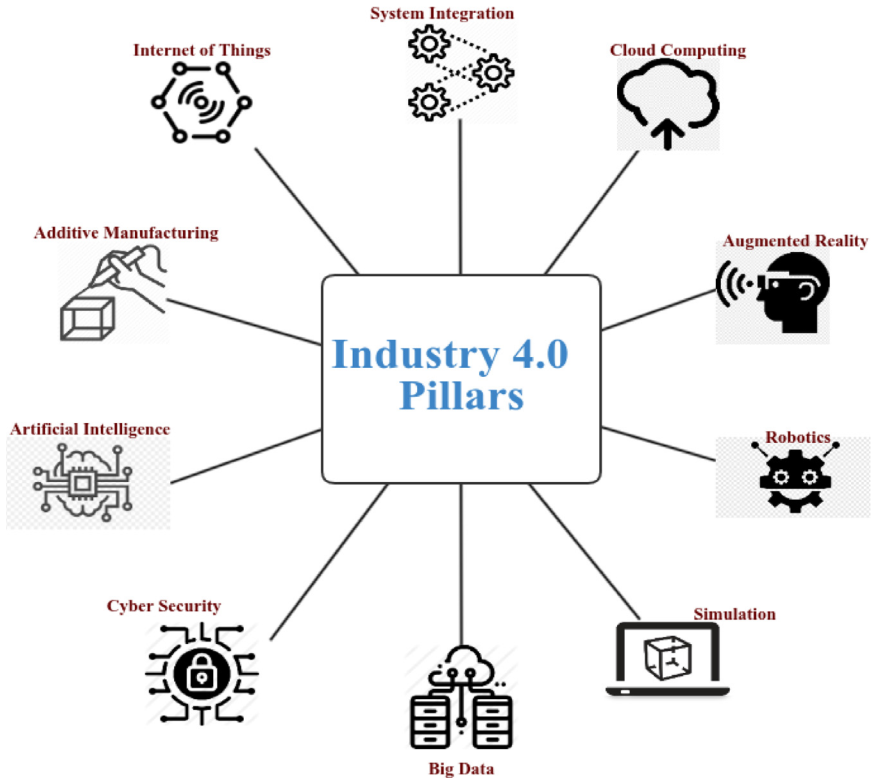

Fig. 1. Pillars of Industry 4.0.

IT, research etc.) and horizontal integration (refers to the integration at levels of production, supply chain, CPSs and enterprise systems).

4. **Cloud computing**: This is one of the most essential pillars for an Industry as it provides a virtual platform for all the IT resources and services which can be accessed from anywhere. The big data collected through various industrial nodes are analyzed and then shifted to the clouds. The industrial network collects Big Data in order to optimize the system performance and send them into the cloud. Industries may utilize three widely used models of cloud computing viz. Software as a service, Infrastructure as a service, and Platform as a service.
5. **Additive manufacturing:** It includes in the physical printing of the models in 3D for visualization and meets the customer requirements. It helps as a prototype of the final product to be built.
6. **Augmented reality (AR):** Augmented Reality bridges the gap between the real-world with the virtual environment. AR helps to explain and portray the real-life complex situations scalable to the original sense. It is very crucial to Industry 4.0 as it empowers engineers to examine the digital information and let it portray in real-world.
7. **Simulation:** It is closely related to the AR in a way that it can be also understood as a virtual space to emulate the real-world industry processes that occur in an industrial environment. Also, and more importantly, simulations help in complex mathematical modeling and algorithms which helps in the overall optimization of the process across the Industry 4.0 ecosystem.
8. **Robotics:** The use of robotics as an autonomous robot helps in the production processes in the Industry 4.0. Simply, they help in the tasks which are difficult to accomplish by a human and thus expedite the production cycle. Moreover, robots may also influence in the growth of the logistics and product distribution activities.
9. **Artificial Intelligence (AI):** Combined with big data and so many machine learning approaches, AI has shown significant potential in several fields. Applied in industrial applications, AI promises for a durable and sustainable performance. Moreover, AI helps in the future predictions of the industrial performance.
10. **Cyber Security:** It is one of the major concerns in the industries to make their system immune to the cyber-attacks. The integrity of whole Industry 4.0 ecosystem is dependent on the protected industrial processes on the cloud and connected environment of IoTs.

Industry 4.0 is thus, a holistic transformation process, beginning with manufacturing, encompassing efficient use of resources, robust supply chains, culminating in personalized customer services (Hermann et al., 2016). At a superficial level, it may seem that industry 4.0 replaces human labor and insights; however, on the contrary, as argued by Wan et al. (2015), human beings form the core of the decision-making process and plays key role in the installation, maintenance, and up-gradation of the whole process. Industry 4.0 thus, exists in synchronization with the human resource system. There has been skepticism that the physical–digital integration can have negative repercussions for the society and the environment because the new system would be overly complex to monitor and administer. However, effective regulations, multi-stakeholders 'approach, open dialogs can prove effective ways to avoid these fallouts (Maynard, 2015).

Over the years, there have been wide-spread works on the overview of Industry 4.0 and various technologies in Industry 4.0 (da Silva et al., 2020; Vianna et al., 2020; Parente et al., 2020). Since the publications in area are increasing every year, there is a need of in-depth bibliometric analysis with respect to "Industry 4.0". Bibliometrics (or Scientometrics) is the discipline that deals with the analysis of published research literature. It basically brings about the core structure of a group of literature by studying its authors, institutions, organizations, references, keywords etc. and creates an aerial picture of the general growth of a research field. The overall notion of scientometrics is based on the works of Eugene Garfield, who in 1960s proposed to develop the information retrieval process resulted in creating the Science Citation index (SCI) (Garfield and Merton, 1979; Wouters, 1999). It has since then been the base of almost all scientometric studies. Various researchers have studied the evolution of many journals using scientometrics, such as, IEEE Transaction on Fuzzy Systems by Yu et al. (2017), Journal of Business Research by Merigó et al. (2015b), Applied Soft Computing by Muhuri et al. (2018), Knowledge-based Systems by Cobo et al. (2015), European Journal of Operational Research (Laengle et al., 2017), Journal of Management by Van Fleet et al. (2006), Neurocomputing by Janmaijaya et al. (2018), Engineering Applications of Artificial Intelligence by Shukla et al. (2019) to name a few.

Numerous studies have been performed to demonstrate the performance of various research areas using scientometric indicators. Some of the key topic specific analysis includes Probability and Statistics by Genest and Guay (2002), Econometric Theory by Baltagi (2007), Fuzzy research by Merigó et al. (2015a), metaheuristics (Ezugwu et al., 2021), Fuzzy Decision Making (Blanco-Mesa et al., 2017), Ant Colony Optimization (Deng and Lin, 2012), Intuitionistic Fuzzy Sets (Yu and Shi, 2015), Real Time Systems (Shukla et al., 2018), automatic clustering algorithms (Ezugwu et al., 2020), type-2 fuzzy sets and systems (Shukla et al., 2020) etc. Other review works related to various applications of fuzzy logic are: intelligent control (Castillo and Melin, 2014), pattern recognition (Melin and Castillo, 2013), design and optimization (Castillo and Melin, 2012) etc. Some of the research areas that have been studied are Management (Podsakoff et al., 2008), Computer Science (Zurita et al., 2017), Physics (Zhou et al., 2014), Mathematics (Behrens and Luksch, 2011) etc. There are only a few bibliometric studies with an aspect of Industry 4.0: Smart factory (Strozzi et al., 2017), production (Kipper et al., 2020), network identification (Da Costa et al., 2019) etc. The motivation of this work comes from the fact that with the rapidly expanding ecosystem of Industry 4.0, we need deeper insights with various computational and machine learning tools. As also can be seen in Fig. 1, Industry 4.0 stands on the top of wide array of domains, impacting almost all the technological landscape. Therefore, an extensive analysis from multiple perspectives is the need of the hour. Moreover, there has not been any comprehensive study which focuses on the publication growth in this area for the last decade. Recently, early publication trends were studied by Muhuri et al. (2019). They performed the bibliometric analysis till October 2017 with only 107 publications in WoS. Since then, there has been a tremendous growth, and it is expanding day by day. The major contributions of this paper are as follows:

1. It establishes and discusses the most crucial pillars of Industry 4.0.
2. It studies the evolution of Industry 4.0 as a research area by creating a bibliometric profile of its publications, identifying the authors, institutions and countries with the most contribution.
3. The in-depth analysis of highly influential authors, countries and institution are also provided.
4. The co-authorship, collaboration and keywords are studied using various visualizations.
5. The top cited papers along with the most cited papers by Industry 4.0 publications are also given along, with the most favored journals.
6. An abstract analysis of various research themes in the publications is performed with the help of k-means clustering algorithm and Latent Dirichlet Allocation (LDA).
7. Concisely, this study tries to provide an aerial picture of the evolution of Industry 4.0 along with highlights.

The paper is organized as follows: Section 2 describes the data and methodology used for this study. Section 3 studies the publications and citation structure of Industry 4.0 publications. Section 4 portrays the most productive and highly influential authors and institutions along with their co-authorship networks. Section 5 contains the analysis of countries publishing Industry 4.0 publications along with a study of its co-authorship network. Section 6 provides an analysis of the keywords. Section 7 show the growth of individual research areas overtime. Section 8 identifies various clusters in the abstracts and LDA is performed to truly bring about the flavor of the clusters. A detailed conclusion and discussions are performed in Section 9.

2. Data and methodology

The data for this study has been collected form the Web of Science (WoS) which is a citation index database maintained by Clarivate Analytics. The Science Citation Index Expanded (SCI-Expanded) and the Social Science Citation Index (SSCI) has been used for the search query. WoS is one of the most reputed databases which is considered as the standard in scientometric studies; other databases include Scopus, Google Scholar etc. The data for this study was collected on 15 January 2020. The search query used was ''TI=Industry 4.0'', for which a total of 1301 results were returned by the search engine. Each entry in the WoS databased is stored as a record with multiple tags such as Author Name (AN), Author Full Name (AF), Title (TI), Source (SO), Abstract (AB) etc. to name a few.

The approach used for this study includes use of scientometric indicators coupled with certain statistical analysis. Co-authorship relationship between author–author, organization–organization and country–country has been explored. A co-authorship network identifies collaborative or co-authorship links. For analysis, the following variables have been used:

(a) Total Papers (TP) – The total number of publications by a source.
(b) Total Citations (TC) – The total number of citations attracted by a source or publication
(c) Citations Per Paper (CPP) – The ratio of TC to TP and it tell the average citation attracted for each publication by a source
(d) Publication Year (PY) – The year of publication of a publication.
(e) Citations Per Year (CPY) – The average number of citations accrued by a publication since its publication.
(f) H-index (Hirsch, 2005) — It is the number of publications (H) which have more than H citations.

The visualization of the networks has been done using the following scientometric tools:

(a) VOSviewer (Van Eck and Waltman, 2010) – It is a scientific tool developed at Lieden University and is used to create and visualize bibliometric networks. The tool has been used to create co-authorship networks between authors, organizations and countries.
(b) Citespace (Chen, 2006) — It is an open-source java tool used to identify and visualize trends in bibliographic data. Citespace has been used to study the keywords of Industry 4.0. Clustering is also performed on the created network. Cluster properties are also discussed.

Table 1 describes the nature of the Industry 4.0 publications. A total of ∼77% of all the extracted publications are articles, ∼8% are classified as review papers and ∼7% as editorial material. The other minor categories are early access (44), proceedings papers (31), news items (5), book chapter (1), and meeting abstract (1).

3. Publication and citation structure of Industry 4.0 publications

In this section, the publication and citation structure of industry 4.0 publications are discussed. The first ever mention of industry 4.0 came in the year 2011 when Kagermann et al. (2011) coined the term describing it as the driving force that blends the virtual and real world with focus on engineering applications. However, according to the data extracted from WoS the first publications was by Jopp (2013) in an editorial of the journal Stahl Und Eisen titled ''*Industry 4.0: The Growing Together of real and virtual Worlds The Internet of Things drives the fourth*

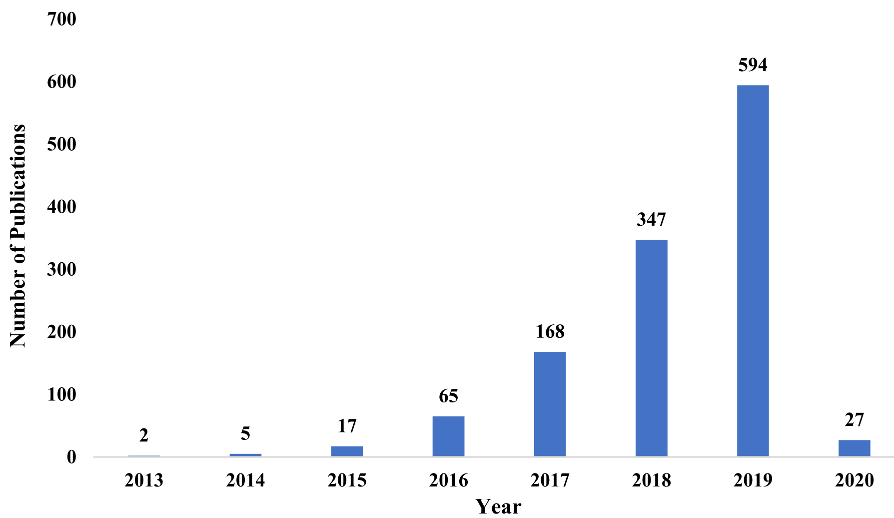

Fig. 2. Distribution of publications.

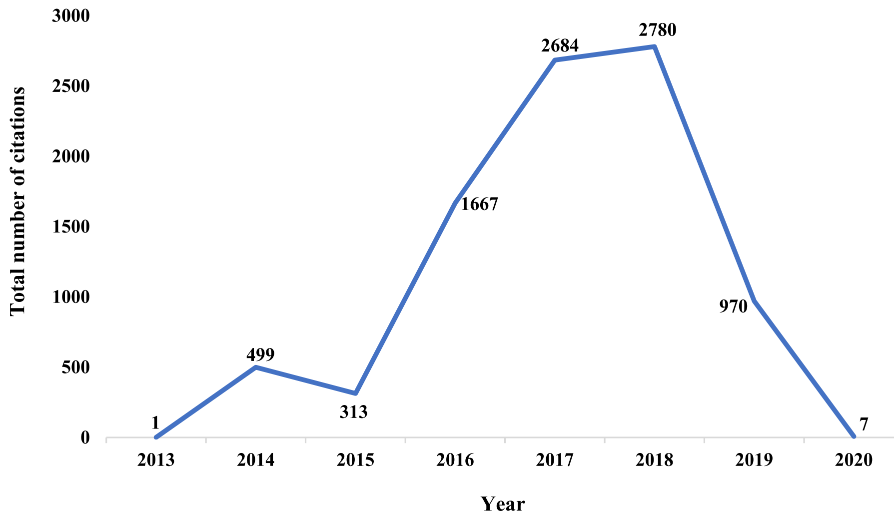

Fig. 3. Year-wise distributions of citations.

Table 1
Nature of publications.

Type of publication	TP
Article	1,005
Review	115
Editorial material	99
Early access	44
Proceedings paper	31
News item	5
Book chapter	1
Meeting abstract	1

industrial Revolution''. The discrepancy in the first mention is due to the fact that WOS is very selective in its index of journals and only high-quality journals are included.

Industry 4.0 has been attraction the attention of research fraternity ever since its introduction. Fig. 2 shows the distribution of the publication over the years. The year 2013 had only 2 publications, however, the number started to rise in the consequent years. Most publications (594) came in the year 2019 which is approximately 48% of the total publications. This exponential increase in the number of publications clearly show that industry 4.0 has been garnering research interest over the years.

The distribution of citations over the time span of 7 years is shown in Fig. 3. The publications of year 2018 have attracted the highest number of citations (2780) followed by the year 2017 with 2684 citations. In 2016, the TC was 1667 while in the year 2019 it was 970. The low TC count of the year 2019 can be attributed to the fact that these publications are fairly young. Table 2 lists the top cited publication of each year. The high number of TC in the year 2018 can be attributed to some of the papers with very high citations such as the paper titled ''Industry 4.0: state of the art and future trends'' by Xu et al. (2018) which attracted 130 citations. For the year 2014, the paper titled ''industry 4.0'' attributed to 465 citations out of the total 499 citations in the year.

Table 3 shows the general citation structure of industry 4.0 publications. Approximately 0.16% of the total publications received more than 200 citations, ∼1% received more than 100 citations, ∼2.6% more than 50 citations, ∼8.9% more than 20 citations and ∼17.6% more than 5 citations. Around ∼61% of the total publications received at least 1 citation and ∼39% did not receive even a single citation. Two papers with more than 200 citations were published in the years 2014 and 2016 by Lasi et al. (2014) and Wang et al. (2016), respectively. It can be concluded from Table 3 that though the publications have received low citations but these publications are fairly young as well and there are good number of publications in the ≥ 20 and ≥ 50 categories. Table 3 also lists year-wise values of TC, TP, CPP and H-index.

Table 2
Top cited publication in each year.

PY	Publication title	TC
2013	Accurate localization technology in fully mechanized coal face: the first step towards coal mining Industry 4.0 (Xu et al., 2013)	4
2014	Industry 4.0 (Lasi et al., 2014)	465
2015	Cloud computing resource scheduling and a survey of its evolutionary Approaches (Zhan et al., 2015)	161
2016	Towards smart factory for industry 4.0: a self-organized multi-agent system with big data-based feedback and coordination (Wang et al., 2016)	265
2017	Intelligent manufacturing in the context of Industry 4.0: A review (Zhong et al., 2017)	173
2018	Industry 4.0: state of the art and future trends (Xu et al., 2018)	130
2019	New IT driven service-oriented smart manufacturing: Framework and characteristics (Tao and Qi, 2017)	53
2020	Digital twin-driven smart manufacturing: Connotation, reference model, applications and research issues (Lu et al., 2020)	2

Table 3
General citation structure of industry 4.0 publications.

Year	≥ 200	≥ 100	≥ 50	≥ 20	≥ 10	≥ 5	≥ 1	0	TP	TC	CPP	H-index
2013	0	0	0	0	0	0	2	0	2	5	2.5	2
2014	1	1	1	2	2	2	3	2	5	499	99.8	3
2015	0	1	2	4	5	8	11	6	17	313	18.4	6
2016	1	5	9	20	31	41	55	10	65	1667	25.6	20
2017	0	5	14	33	67	99	150	18	168	2684	16.0	25
2018	0	1	6	41	90	157	280	67	347	2780	8.0	25
2019	0	0	1	9	21	51	245	340	585	970	1.7	13
2020	0	0	0	0	0	1	5	31	36	7	0.2	2
Total	2	13	33	109	216	359	751	474	1225			
Percentage	0.16	1.06	2.69	8.90	17.63	29.31	61.31	38.69				

The top 50 Industry 4.0 publications are listed in Table 4 which are sorted by TC and listed Rank (R) wise. The publication with the highest number of citations is titled *"Industry 4.0"* by Lasi et al. (2014) and published in Business & Information Systems Engineering. The paper has received 465 citations since its publication in the year 2014. The authors in this paper give an over view of Industry 4.0 and explains the fundamental concepts of the domain such as smart factory, cyber physical systems, smart manufacturing etc. The second most cited paper is by Wang et al. (2016) published in Computer Networks with 265 citations and titled *"Towards smart factory for industry 4.0: a self-organized multi-agent system with big data-based feedback and coordination"*. In this paper the authors present a smart factory framework. The third spot is taken by the publication in the International Journal of Precision Engineering and Manufacturing-Green Technology by Kang et al. (2016) titled *"Smart Manufacturing: Past Research, Present Findings, and Future Directions"* wherein the authors provide a review of literature in smart manufacturing. They are followed by Wan et al. (2016a), Zhong et al. (2017) and Liao et al. (2017) for their works on "*Software-Defined Industrial Internet of Things in the Context of Industry 4.0", "Intelligent Manufacturing in the Context of Industry 4.0: A Review"* and *"Past, present and future of Industry 4.0-a systematic literature review and research agenda proposal"* respectively.

In terms of CPY the paper by Lasi et al. (2014) again performed best with 77.5 CPY followed by Wang et al. (2016) and Xu et al. (2018) with 66.3 and 65 CPY, respectively. In contrast to the top cited publications, Table 5 lists the top 40 most cited references (documents) by the Industry 4.0 publications. VOSviewer has been used to explore this particular attribute, wherein co-citation analysis of the publications is performed to identify the top cited references.

Now, we discuss the most favored journals or the journals that have published the most number of industry 4.0 research publications. Table 6 list the top 20 most favored journals sorted by TP. The h-index and TC of the publications is also mentioned. IEEE Access which is an open access journal published by IEEE has published the highest number of publications (TP=73), followed by the International Journal of Production Research with 53 publications. The third position is taken by Sustainability with 47 publications.

However, when considering the citations, the International Journal of Production Research tops the list with 944 citations and H-index of 14. IEEE Access also sits along with a H-index of 14 but a TC of 758. Almost all the journals in Table 6 publishes interdisciplinary research with a broader extent. Thereby, it can be concluded that industry 4.0 research has shown its presence in a wide spectrum of domains even in its early budding years.

4. Authors and Institution analysis

In this section, the authors and institutions analysis are done in terms of scientometric indicators. Highly cited and influential authors and institutions are also discussed along with their co-authorship network.

4.1. Authorship

The most productive authors are given in Table 7. The authors' list is sorted on the basis of TP. The highest contribution has been from Li D and Wan JF with 20 papers each. However, Wan JF has a greater number of citations. The third sport is taken by Wang SY with 12 publications and a H-index of 9. These three authors have one thing in common i.e. they belong to the same research group and published several papers including "*Towards smart factory for industry 4.0: a self-organized multi-agent system with big data-based feedback and coordination*" which has 265 citations. The next spot in the list is taken by Xu X with 11 publications and TC of 326 out of which 173 citations belong to one publication titled "*Intelligent Manufacturing in the Context of Industry 4.0: A Review*". The fifth and sixth position is held by Fernandez Carames TM and Fraga-Lamas P with 10 publications and a H-index of 7; they both belong to the same research group and their most cited publication is titled "*A Review on Industrial Augmented Reality Systems for the Industry 4.0 Shipyard*".

Table 4
Top 50 most cited Industry 4.0 publications.

R	Publication title	Author's name	Journal	PY	TC	CPY
1	Industry 4.0 (Lasi et al., 2014)	Lasi H; Kemper HG; Fettke P; Feld T; Hoffmann M	Business & Information Systems Engineering	2014	465	77.5
2	Towards smart factory for industry 4.0: a self-organized multi-agent system with big data based feedback and coordination (Wang et al., 2016)	Wang SY; Wan JF; Zhang DQ; Li D; Zhang CH	Computer Networks	2016	265	66.3
3	Smart Manufacturing: Past Research, Present Findings, and Future Directions (Kang et al., 2016)	Kang HS; Lee JY; Choi S; Kim H; Park JH; Son JY; Kim BH; Noh SD	International Journal of Precision Engineering and Manufacturing-Green Technology	2016	191	47.8
4	Software-Defined Industrial Internet of Things in the Context of Industry 4.0 (Wan et al., 2016a)	Wan JF; Tang SL; Shu ZG; Li D; Wang SY; Imran M; Vasilakos AV	IEEE Sensors Journal	2016	182	45.5
5	Intelligent Manufacturing in the Context of Industry 4.0: A Review (Zhong et al., 2017)	Zhong RY; Xu X; Klotz E; Newman ST	Engineering	2017	173	57.7
6	Past, present and future of Industry 4.0-a systematic literature review and research agenda proposal (Liao et al., 2017)	Liao YX; Deschamps F; Loures EDR; Ramos LFP	International Journal of Production Research	2017	171	57.0
7	Industry 4.0 and the current status as well as future prospects on logistics (Hofmann and Rüsch, 2017)	Hofmann E; Rusch M	Computers in Industry	2017	166	55.3
8	Cloud Computing Resource Scheduling and a Survey of Its Evolutionary Approaches (Zhan et al., 2015)	Zhan ZH; Liu XF; Gong YJ; Zhang J; Chung HSH; Li Y	ACM Computing Surveys	2015	161	32.2
9	Industry 4.0: state of the art and future trends (Xu et al., 2018)	Xu LD; Xu EL; Li L	International Journal of Production Research	2018	130	65.0
10	A review of industrial wireless networks in the context of Industry 4.0 (Li et al., 2017)	Li XM; Li D; Wan JF; Vasilakos AV; Lai CF; Wang SY	Wireless Networks	2017	122	40.7
11	A dynamic model and an algorithm for short-term supply chain scheduling in the smart factory industry 4.0 (Ivanov et al., 2016)	Ivanov D; Dolgui A; Sokolov B; Werner F; Ivanova M	International Journal of Production Research	2016	112	28.0
12	Blockchain technology in the chemical industry: Machine-to-machine electricity market (Sikorski et al., 2017)	Sikorski JJ; Haughton J; Kraft M	Applied Energy	2017	108	36.0
13	Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry (Oesterreich and Teuteberg, 2016)	Oesterreich TD; Teuteberg F	Computers in Industry	2016	104	26.0
14	Fog of Everything: Energy-Efficient Networked Computing Architectures, Research Challenges, and a Case Study (Baccarelli et al., 2017)	Baccarelli E; Naranjo PGV; Scarpiniti M; Shojafar M; Abawajy JH	IEEE Access	2017	91	30.3
15	A Manufacturing Big Data Solution for Active Preventive Maintenance (Wan et al., 2017)	Wan JF; Tang SL; Li D; Wang SY; Liu CL; Abbas H; Vasilakos AV	IEEE Transactions on Industrial Informatics	2017	76	25.3
16	SDMSim: A manufacturing service supply–demand matching simulator under cloud environment (Tao et al., 2017)	Tao F; Cheng JF; Cheng Y; Gu SX; Zheng TY; Yang H	Robotics and Computer-Integrated Manufacturing	2017	75	25.0
17	The concept and progress of intelligent spindles: A review (Cao et al., 2017)	Cao HR; Zhang XW; Chen XF	International Journal of Machine Tools & Manufacture	2017	74	24.7
18	Smart Factory of Industry 4.0: Key Technologies, Application Case, and Challenges (Chen et al., 2017)	Chen BT; Wan JF; Shu L; Li P; Mukherjee M; Yin BX	IEEE Access	2018	65	32.5
19	Industry 4.0 as a Cyber-Physical System study (Mosterman and Zander, 2016)	Mosterman PJ; Zander J	Software and Systems Modeling	2016	65	16.3

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Table 4 (*continued*).

R	Publication title	Author's name	Journal	PY	TC	CPY
20	Continuous maintenance and the future - Foundations and technological challenges (Roy et al., 2016)	Roy R; Stark R; Tracht K; Takata S; Mori M	CIRP Annals-Manufacturing Technology	2016	64	16.0
21	Morphology Development in Solution-Processed Functional Organic Blend Films: An In Situ Viewpoint (Richter et al., 2017)	Richter LJ; DeLongchamp DM; Amassian A	Chemical Reviews	2017	61	20.3
22	An event-driven manufacturing information system architecture for Industry 4.0 (Theorin et al., 2017)	Theorin A; Bengtsson K; Provost J; Lieder M; Johnsson C; Lundholm T; Lennartson B	International Journal of Production Research	2017	61	20.3
23	The industrial management of SMEs in the era of Industry 4.0 (Moeuf et al., 2018)	Moeuf A; Pellerin R; Lamouri S; Tamayo-Giraldo S; Barbaray R	International Journal of Production Research	2018	59	29.5
24	Digital Twin Shop-Floor: A New Shop-Floor Paradigm Towards Smart Manufacturing (Tao and Zhang, 2017)	Tao F; Zhang M	IEEE Access	2017	59	19.7
25	Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison (Qi and Tao, 2018)	Qi QL; Tao F	IEEE Access	2018	58	29.0
26	Smart manufacturing systems for Industry 4.0: Conceptual framework, scenarios, and future perspectives (Zheng et al., 2018)	Zheng P; Wang HH; Sang ZQ; Zhong RY; Liu YK; Liu C; Mubarok K; Yu SQ; Xu X	Frontiers of Mechanical Engineering	2018	57	28.5
27	What Drives the Implementation of Industry 4.0? The Role of Opportunities and Challenges in the Context of Sustainability (Müller et al., 2018b)	Muller JM; Kiel D; Voigt KI	Sustainability	2018	54	27.0
28	New IT Driven Service-Oriented Smart Manufacturing: Framework and Characteristics (Tao and Qi, 2017)	Tao F; Qi QL	IEEE Transactions on Systems Man Cybernetics-Systems	2019	53	53.0
29	Industry 4.0 and Cloud Manufacturing: A Comparative Analysis (Liu and Xu, 2017)	Liu YK; Xu X	Journal of Manufacturing Science and Engineering-Transactions of the ASME	2017	52	17.3
30	Learning factories for future oriented research and education in manufacturing (Abele et al., 2017)	Abele E; Chryssolouris G; Sihn W; Metternich J; ElMaraghy H; Seliger G; Sivard G; ElMaraghy W; Hummel V; Tisch M; Seifermann S	CIRP Annals-Manufacturing Technology	2017	52	17.3
31	Industry 4.0-Prerequisites and Visions (Vogel-Heuser and Hess, 2016)	Vogel-Heuser B; Hess D	IEEE Transactions on Automation Science and Engineering	2016	52	13.0
32	Cloud-assisted industrial cyber-physical systems: An insight (Yue et al., 2015)	Yue XJ; Cai H; Yan HH; Zou CF; Zhou KL	Microprocessors and Microsystems	2015	51	10.2
33	Engineering Methods and Tools for Cyber-Physical Automation Systems (Harrison et al., 2016)	Harrison R; Vera D; Ahmad B	Proceedings of the IEEE	2016	50	12.5
34	Circular economy meets industry 4.0: Can big data drive industrial symbiosis? (Tseng et al., 2018)	Tseng ML; Tan RR; Chiu ASF; Chien CF; Kuo TC	Resources Conservation and Recycling	2018	48	24.0
35	A Review of Technology Standards and Patent Portfolios for Enabling Cyber-Physical Systems in Advanced Manufacturing (Trappey et al., 2016)	Trappey AJC; Trappey CV; Govindarajan UH; Sun JJ; Chuang AC	IEEE Access	2016	45	11.3
36	The evolution of production systems from Industry 2.0 through Industry 4.0 (Yin et al., 2018)	Yin Y; Stecke KE; Li DN	International Journal of Production Research	2018	44	22.0

(*continued on next page*)

In terms of CPP, Wang SY outranks everyone in the list with a CPP of 63.6 followed by Zhang CH (50). Table 8 lists the most influential authors in terms of citations attracted by their publications. Comparing Table 8 with Table 7, it can be seen that there are only 4 new additions with TC as less as 5 papers. Thereby pointing out the high influence of some authors with very less publications.

It can be clearly deduced from the above analysis that the top 15 authors list is composed of several groups that work in collaboration. One such big group includes the authors Li D, Wan JF, Wang SY and

Table 4 (*continued*).

R	Publication title	Author's name	Journal	PY	TC	CPY
37	Multi-dimensional data indexing and range query processing via Voronoi diagram for internet of things (Wan et al., 2019)	Wan SH; Zhao Y; Wang T; Gu ZH; Abbasi QH; Choo KKR	Future Generation Computer Systems-The International Journal of EScience	2019	43	43.0
38	Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations (De Sousa Jabbour et al., 2018)	Jabbour ABLD; Jabbour CJC; Godinho M; Roubaud D	Annals of Operations Research	2018	43	21.5
39	Internet of Things and Edge Cloud Computing Roadmap for Manufacturing (Georgakopoulos et al., 2016)	Georgakopoulos D; Jayaraman PP; Fazia M; Villari M; Ranjan R	IEEE Cloud Computing	2016	42	10.5
40	Smart operators in industry 4.0: A human-centered approach to enhance operators' capabilities and competencies within the new smart factory context (Longo et al., 2017)	Longo F; Nicoletti L; Padovano A	Computers & Industrial Engineering	2017	40	13.3
41	A review of essential standards and patent landscapes for the Internet of Things: A key enabler for Industry 4.0 (Trappey et al., 2017)	Trappey AJC; Trappey CV; Govindarajan UH; Chuang AC; Sun JJ	Advanced Engineering Informatics	2017	40	13.3
42	Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies (Tortorella and Fettermann, 2018)	Tortorella GL; Fettermann D	International Journal of Production Research	2018	39	19.5
43	Mobile Services for Customization Manufacturing Systems: An Example of Industry 4.0 (Wan et al., 2016b)	Wan JF; Yi ML; Li D; Zhang CH; Wang SY; Zhou KL	IEEE Access	2016	39	9.8
44	A Review on Industrial Augmented Reality Systems for the Industry 4.0 Shipyard (Fraga-Lamas et al., 2018)	Fraga-Lamas P; Fernandez-Carames TM; Blanco-Novoa O; Vilar-Montesinos MA	IEEE Access	2018	38	19.0
45	Working together: A Review on Safe Human-Robot Collaboration in Industrial Environments (Robla-Gómez et al., 2017)	Robla-Gomez S; Becerra VM; Llata JR; Gonzalez-Sarabia E; Torre-Ferrero C; Perez-Oria J	IEEE Access	2017	38	12.7
46	Literature review on the 'Smart Factory' concept using bibliometric tools (Strozzi et al., 2017)	Strozzi F; Colicchia C; Creazza A; Noe C	International Journal of Production Research	2017	38	12.7
47	Industrial Internet of Things: Challenges, Opportunities, and Directions (Sisinni et al., 2018)	Sisinni E; Saifullah A; Han S; Jennehag U; Gidlund M	IEEE Transactions on Industrial Informatics	2018	37	18.5
48	Discrete Event Simulation and Virtual Reality Use in Industry: New Opportunities and Future Trends (Turner et al., 2016)	Turner CJ; Hutabarat W; Oyekan J; Tiwari A	IEEE Transactions on Human-Machine Systems	2016	37	9.3
49	UML4IoT-A UML-based approach to exploit IoT in cyber-physical manufacturing systems (Thramboulidis and Christoulakis, 2016)	Thramboulidis K; Christoulakis F	Computers in Industry	2016	37	9.3
50	Deploying Fog Computing in Industrial Internet of Things and Industry 4.0 (Aazam et al., 2018)	Aazam M; Zeadally S; Harras KA	IEEE Transactions on Industrial Informatics	2018	36	18.0

Zhang CH. Another group includes Fernandez Carames and TM Fraga-Lamas P. The third group includes Sanin C and Szczerbicki E. This fact can also be corroborated from Fig. 4 which visualizes the co-authorship network of authors. Each node represents an author and the size of the node is relative to the number of documents it represents. Any collaboration between two nodes is represented by a line connecting the two. Fig. 4 includes all the authors with 5 or more publications and a total of 55 authors have been considered. Multiple nodes with high cohesion represent a cluster, thereby signifying high collaboration between them. The color of a node signifies to which cluster it belongs. There are multiple groups that work in collaborations, however, the inter cluster co-authorship is extremely low as the network contains a lot of disconnected small networks. Li D is the most collaborative author with a total link strength of 55. Wan J is second with total link strength of 51, followed by Wang SY (33), Liu C (32) and Imran M (23).

4.2. Most productive and influential organizations

The institution-wise ordering is displayed in Table 9. It shows the total publications, total citations and H-index of institutions. Table 9 also presents the most productive institutions which have contributed to Industry 4.0 publications. The South China University of technology takes the top position with 31 publications. The second position is taken by Shanghai Jiao Tong University with 24 publications. The third spot is taken by Centre National De La Recherche Scientifique (CNRS) with 22 publications. It can be observed that the institutions from China have been more productive.

In terms of TC and H-index, the South China University again sits at the top with 958 citations and 12 h-index with the most cited publication being "*Towards smart factory for industry 4.0: a self-organized multi-agent system with big data-based feedback and coordination*" authored by Wang et al. (2016) attracting a total of 265 citations. In terms of H-index (9), the next spot is taken by CNRS with a TC of 342

Table 5
Top 50 most cited references by Industry 4.0 publications.

R	Title	Authors	Source	PY	TC
1	A cyber-physical systems architecture for industry 4.0-based manufacturing systems (Lee et al., 2015)	Lee, J., Bagheri, B., & Kao, H. A.	Manufacturing Letters	2015	170
2	Industry 4.0 (Lasi et al., 2014)	Lasi, H., Fettke, P., Kemper, H. G., Feld, T., & Hoffmann, M.	Business & Information Systems Engineering	2014	115
3	Implementation of recommendations for the future project Industrie 4.0 (Kagermann et al., 2013)	Kagermann, H., Wahlster, W., & Helbig, J.	German Federal Ministry of Education and Research	2013	114
4	Service innovation and smart analytics for industry 4.0 and big data environment (Lee et al., 2014)	Lee, J., Kao, H. A., & Yang, S.	Procedia CIRP	2014	96
5	Towards smart factory for industry 4.0: a self-organized multi-agent system with big data based feedback and coordination (Wang et al., 2016)	Wang, S., Wan, J., Zhang, D., Li, D., & Zhang, C.	Computer Networks	2016	90
6	Design principles for industrie 4.0 scenarios (Hermann et al., 2016)	Hermann, M., Pentek, T., & Otto, B.	Hawaii International Conference on System Sciences	2016	81
7	Opportunities of sustainable manufacturing in industry 4.0 (Stock and Seliger, 2016)	Stock, T., & Seliger, G.	Procedia CIRP	2016	80
8	How virtualization, decentralization and network building change the manufacturing landscape: An Industry 4.0 Perspective (Brettel et al., 2014)	Brettel, M., Friederichsen, N., Keller, M., & Rosenberg, M.	International Journal of Mechanical, Industrial Science and Engineering	2014	74
9	Past, present and future of Industry 4.0-a systematic literature review and research agenda proposal (Liao et al., 2017)	Liao, Y., Deschamps, F., Loures, E. D. F. R., & Ramos, L. F. P.	International Journal of Production Research	2017	72
10	Industry 4.0: A survey on technologies, applications and open research issues (Lu, 2017)	Lu, Y.	Journal of Industrial Information Integration	2017	71
11	From cloud computing to cloud manufacturing (Xu, 2012)	Xu, X.	Robotics and Computer-Integrated Manufacturing	2012	70
12	Cyber-physical production systems: Roots, expectations and R&D challenges (Monostori, 2014)	Monostori, L.	Procedia CIRP	2014	62
13	Internet of things in industries: A survey (Da Xu et al., 2014)	Da Xu, L., He, W., & Li, S.	IEEE Transactions on Industrial Informatics	2014	62
14	Cyber-physical systems in manufacturing (Monostori et al., 2016)	Monostori, L., Kádár, B., Bauernhansl, T., Kondoh, S., Kumara, S., Reinhart, G., & Ueda, K.	CIRP Annals	2016	59
15	Smart manufacturing: Past research, present findings, and future directions (Kang et al., 2016)	Kang, H. S., Lee, J. Y., Choi, S., Kim, H., Park, J. H., Son, J. Y., & Do Noh, S.	International Journal of Precision Engineering and Manufacturing-Green Technology	2016	59
16	Industry 4.0 and the current status as well as future prospects on logistics (Hofmann and Rüsch, 2017)	Hofmann, E., & Rüsch, M.	Computers in Industry	2017	58
17	Intelligent manufacturing in the context of industry 4.0: a review (Zhong et al., 2017)	Zhong, R. Y., Xu, X., Klotz, E., & Newman, S. T.	Engineering	2017	52
18	Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry (Oesterreich and Teuteberg, 2016)	Oesterreich, T. D., & Teuteberg, F.	Computers in Industry	2016	48
19	The future of industrial communication: Automation networks in the era of the internet of things and industry 4.0 (Wollschlaeger et al., 2017)	Wollschlaeger, M., Sauter, T., & Jasperneite, J.	IEEE Industrial Electronics Magazine	2017	47
20	The internet of things: A survey (Atzori et al., 2010)	Atzori, L., Iera, A., & Morabito, G.	Computer Networks	2010	46
21	Industrie 4.0: Hit or hype?[industry forum] (Drath and Horch, 2014)	Drath, R., & Horch, A.	IEEE Industrial Electronics Magazine	2014	45
22	Standardization as as the crucial crucial challenge challenge Towards Standardization as the crucial challenge for highly production systems for highly modular, multi-vendor production systems for highly modular, multi-vendor production (Weyer et al., 2015)	Weyer, S., Schmitt, M., Ohmer, M., Gorecky, D., Weyer, S., Schmitt, M., & Gorecky, D.	IFAC-Papers Online	2015	45

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and their most cited paper is jointly published with Otto Von Guericke University, which is titled as "*A dynamic model and an algorithm for short-term supply chain scheduling in the smart factory industry 4.0*", attracting a total of 112 citations. Table 10 lists the top 15 influential

Table 5 (*continued*).

R	Title	Authors	Source	PY	TC
23	Smart manufacturing: Past research, present findings, and future directions (Kang et al., 2016)	Kang, H. S., Lee, J. Y., Choi, S., Kim, H., Park, J. H., Son, J. Y., & Do Noh, S.	International Journal of Precision Engineering and Manufacturing-Green Technology	2016	44
24	Current status and advancement of cyber-physical systems in manufacturing (Wang et al., 2015)	Wang, L., Törngren, M., & Onori, M.	Journal of Manufacturing Systems	2015	44
25	Internet of Things (IoT: A vision, architectural elements, and future directions (Gubbi et al., 2013)	Gubbi, J., Buyya, R., Marusic, S., & Palaniswami, M.	Future Generation Computer Systems	2013	42
26	Cyber physical systems: Design challenges (Lee, 2008)	Lee, E. A.	IEEE International Symposium on Object and Component-Oriented Real-Time Distributed Computing	2008	42
27	Software-defined industrial internet of things in the context of industry 4.0 (Wan et al., 2016a)	Wan, J., Tang, S., Shu, Z., Li, D., Wang, S., Imran, M., & Vasilakos, A. V.	IEEE Sensors Journal	2016	42
28	Visual computing as a key enabling technology for industrie 4.0 and industrial internet (Posada et al., 2015)	Posada, J., Toro, C., Barandiaran, I., Oyarzun, D., Stricker, D., de Amicis, R., & Vallarino, I.	IEEE Computer Graphics and Applications	2015	41
29	Smart factories in Industry 4.0: A review of the concept and of energy management approached in production based on the Internet of Things paradigm (Shrouf et al., 2014)	Shrouf, F., Ordieres, J., & Miragliotta, G.	IEEE International Conference on Industrial Engineering and Engineering Management	2014	38
30	A dynamic model and an algorithm for short-term supply chain scheduling in the smart factory industry 4.0 (Ivanov et al., 2016)	Ivanov, D., Dolgui, A., Sokolov, B., Werner, F., & Ivanova, M.	International Journal of Production Research	2016	37
31	Big Data and virtualization for manufacturing cyber-physical systems: A survey of the current status and future outlook (Babiceanu and Seker, 2016)	Babiceanu, R. F., & Seker, R.	Computers in Industry	2016	36
32	A maturity model for assessing Industry 4.0 readiness and maturity of manufacturing enterprises (Schumacher et al., 2016)	Schumacher, A., Erol, S., & Sihn, W.	Procedia CIRP	2016	36
33	Human-machine-interaction in the industry 4.0 era (Gorecky et al., 2014)	Gorecky, D., Schmitt, M., Loskyll, M., & Zühlke, D.	IEEE International Conference on Industrial Informatics	2014	34
34	How smart connected devices are transforming competition (Porter and Heppelmann, 2014)	Porter, M. E., & Heppelmann, J. E.	Harvard Business Review	2014	34
35	A categorical framework of manufacturing for industry 4.0 and beyond (Qin et al., 2016)	Qin, J., Liu, Y., & Grosvenor, R.	Procedia CIRP	2016	33
36	Industry 4.0: state of the art and future trends (Xu et al., 2018)	Xu, L. D., Xu, E. L., & Li, L.	International Journal of Production Research	2018	33
37	Smart manufacturing (Kusiak, 2018)	Kusiak, A.	International Journal of Production Research	2018	31
38	What drives the implementation of Industry 4.0? The role of opportunities and challenges in the context of sustainability (Müller et al., 2018b)	Müller, J. M., Kiel, D., & Voigt, K. I.	Sustainability	2018	31
39	Fortune favors the prepared: How SMEs approach business model innovations in Industry 4.0 (Müller et al., 2018a)	Müller, J. M., Buliga, O., & Voigt, K. I.	Technological Forecasting and Social Change	2018	30
40	"Industrie 4.0" and smart manufacturing-a review of research issues and application examples (Thoben et al., 2017)	Thoben, K. D., Wiesner, S., & Wuest, T.	International Journal of Automation Technology	2017	30
41	The industrial management of SMEs in the era of Industry 4.0 (Moeuf et al., 2018)	Moeuf, A., Pellerin, R., Lamouri, S., Tamayo-Giraldo, S., & Barbaray, R.	International Journal of Production Research	2018	29
42	The smart factory: exploring adaptive and flexible manufacturing solutions (Radziwon et al., 2014)	Radziwon, A., Bilberg, A., Bogers, M., & Madsen, E. S.	Procedia Engineering	2014	29
43	SmartFactory—Towards a factory-of-things (Zuehlke, 2010)	Zuehlke, D.	Annual Reviews in Control	2010	29
44	Smart manufacturing, manufacturing intelligence and demand-dynamic performance (Davis et al., 2012)	Davis, J., Edgar, T., Porter, J., Bernaden, J., & Sarli, M.	Computers & Chemical Engineering	2012	28

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Table 5 (*continued*).

R	Title	Authors	Source	PY	TC
45	Lean Automation enabled by Industry 4.0 Technologies (Kolberg and Zühlke, 2015)	Kolberg, D., & Zühlke, D.	IFAC-Papers Online	2015	28
46	A review of industrial wireless networks in the context of Industry 4.0 (Li et al., 2017)	Li, X., Li, D., Wan, J., Vasilakos, A. V., Lai, C. F., & Wang, S.	Wireless Networks	2017	28
47	A complex view of industry 4.0 (Roblek et al., 2016)	Roblek, V., Meško, M., & Krapež, A.	Sage Open	2016	28
48	Making existing production systems Industry 4.0-ready (Schlechtendahl et al., 2015)	Schlechtendahl, J., Keinert, M., Kretschmer, F., Lechler, A., & Verl, A.	Production Engineering	2015	28
49	Change through digitization—Value creation in the age of Industry 4.0 (Kagermann, 2015)	Kagermann, H.	Management of Permanent Change	2015	27
50	Recent advances and trends in predictive manufacturing systems in big data environment (Lee et al., 2013)	Lee, J., Lapira, E., Bagheri, B., & Kao, H. A.	Manufacturing Letters	2013	27

Table 6
Most Favored journals.

R	Source	TP	H-index	TC
1	IEEE Access	73	14	758
2	International Journal of Production Research	53	14	944
3	Sustainability	47	9	234
4	International Journal of Advanced Manufacturing Technology	46	5	84
5	Sensors	43	7	162
6	Computers in Industry	39	11	517
7	IEEE Transactions on Industrial Informatics	31	11	352
8	International Journal of Computer Integrated Manufacturing	29	5	91
9	Applied Sciences BASEL	25	4	44
10	Dyna	22	2	10
11	At Automatisierungstechnik	21	4	56
12	Computers Industrial Engineering	21	6	132
13	Journal of Manufacturing Systems	19	8	137
14	Processes	18	7	114
15	Robotics and Computer Integrated Manufacturing	18	5	162
16	Advanced Engineering Informatics	13	3	74
17	Fleischwirtschaft	12	1	1
18	Future Generation Computer Systems The International Journal of EScience	12	5	93
19	South African Journal of Industrial Engineering	12	2	27
20	CIRP Annals Manufacturing Technology	11	7	197

Table 7
Most Productive authors.

R	Author name	TP	TC	H-index	CPP
1	Li D	20	852	11	42.6
2	Wan JF	20	895	11	44.8
3	Wang SY	12	763	9	63.6
4	Xu X	11	326	5	29.6
5	Fernandez-Carames TM	10	173	7	17.3
6	Fraga-Lamas P	10	173	7	17.3
7	Liu CL	10	208	8	20.8
8	Chien CF	9	87	5	9.7
9	Tao F	9	291	7	32.3
10	Imran M	7	261	5	37.3
11	Ivanov D	7	173	4	24.7
12	Mourtzis D	7	34	4	4.9
13	Sanin C	7	62	2	8.9
14	Szczerbicki E	7	62	2	8.9
15	Zhang CH	7	350	6	50.0

institutions where South China University of Technology, China again tops the list with 958 citations. Second spot University of Stuttgart, Germany has only 7 papers with a TC of 485, also making it the higher CPP of 69.3.

Fig. 5 shows the co-authorship network of institution. Here it can be seen that the network of nodes is divided in to two halves, a connected half on the left and a disconnected half on the right. The left half of Fig. 5 is the largest connected component with 72 nodes i.e., all the nodes in this half have at least one collaboration with another node in this half. The other half consists of node with zero link strength which suggest no collaboration by the institutions. South China university of technology is the most collaborative institution with a link strength of 38. Shanghai Jiao Tong University follows with a link strength of 28. Beihang University and King Saud University are at the third position with a link strength of 16. Chinese Academy of Sciences is at the fourth position with a link strength of 15, followed by Nanyang Technological University (11). The link strength of the node in contention is the count of the nodes with which it is directly connected with, thus link strength directly signifies the collaborations by an institution. Institutions with high cohesion have been assigned to same cluster. An interesting fact to notice from figure is the region wise diversity of collaboration.

Table 8
Most influential authors.

R	Author name	TP	TC	CPP
1	Wan JF	20	895	44.8
2	Li D	20	852	42.6
3	Wang SY	12	763	63.6
4	Zhang CH	7	350	50.0
5	Xu X	10	326	32.6
6	Tang S	5	294	58.8
7	Tao F	9	291	32.3
8	Imran M	7	261	37.3
9	Zhong R Y	5	236	47.2
10	Liu CL	10	208	20.8
11	Li Y	5	194	38.8
12	Fernandez-Carames, TM.	10	173	17.3
13	Fraga-Lamas P	10	173	17.3
14	Ivanov D	7	173	24.7
15	Dolgui A	6	162	27.0

Table 9
Most productive organizations.

R	Organization	Country	TP	TC	H -index	CPP
1	South China University of Technology	China	31	958	12	30.9
2	Shanghai Jiao Tong University	China	24	256	8	10.7
3	Centre National De La Recherche Scientifique CNRS	France	22	342	9	15.5
4	University Of Basque Country	Spain	18	59	4	3.3
5	University Of Naples Federico Ii	Italy	17	71	4	4.2
6	Nanyang Technological University	Singapore	16	179	4	11.2
7	Beihang University	China	14	357	8	25.5
8	Otto Von Guericke University	Germany	14	171	4	12.2
9	National Tsing Hua University	Taiwan	13	186	7	14.3
10	Chinese Academy Of Sciences	China	12	35	4	2.9
11	National Chiao Tung University	Taiwan	12	170	7	14.2
12	Tecnologico De Monterrey	Mexico	12	76	4	6.3
13	Universidade Da Coruna	Spain	12	173	7	14.4
14	King Saud University	Saudi Arabia	11	340	6	30.9
15	Royal Institute Of Technology	Sweden	11	140	4	12.7

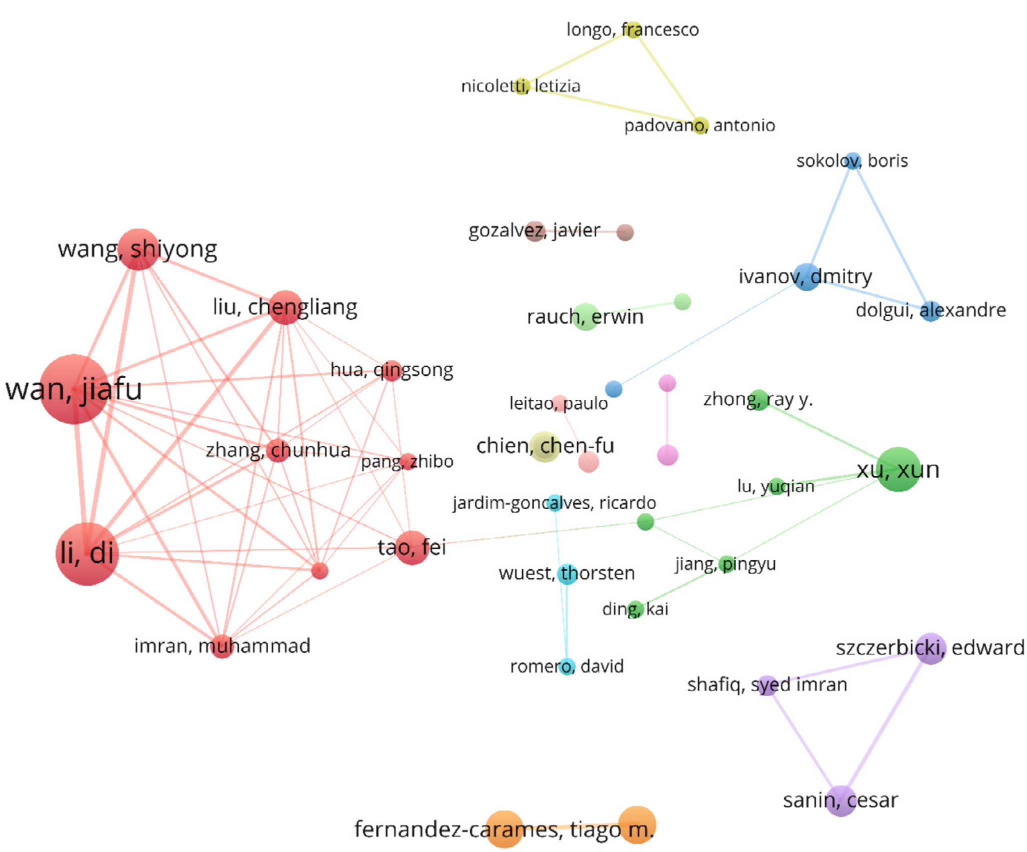

Fig. 4. Co-authorship network of authors.

Table 10
Most influential organizations.

R	Organization name	TP	TC	CPP
1	South China University of Technology, China	31	958	30.9
2	University of Stuttgart, Germany	7	485	69.3
3	LuleåUniversity of Technology, Sweden	9	441	49.0
4	Beihang University, China	14	357	25.5
5	King Saud University, Saudi Arabia	11	340	30.9
6	University of Auckland, New Zealand	11	326	29.6
7	Tongji University, China	5	282	56.4
8	Shanghai Jiao Tong University, China	24	256	10.7
9	University of Glasgow, Scotland	6	227	37.8
10	National Tsing Hua University, Taiwan	13	186	14.3
11	Nanyang Technological University, Singapore	16	179	11.2
12	Berlin School of Economics and Law, Germany	7	173	24.7
13	University of A Coruña, Spain	12	173	14.4
14	National Chiao Tung University, Taiwan	12	170	14.2
15	Jiangxi University of Science and Technology, China	5	168	33.6

Table 11
Top 25 most productive countries.

Rank	Country/Territory	TP	H	TC
1	China	191	24	2350
2	Germany	176	20	1839
3	Italy	130	14	713
4	USA	118	16	1035
5	Spain	114	13	536
6	England	109	16	1077
7	Taiwan	67	8	496
8	Brazil	53	9	424
9	India	47	10	273
10	France	43	11	462
11	Australia	40	9	285
12	Sweden	38	12	678
13	Poland	36	3	87
14	Portugal	36	8	166
15	South Korea	34	7	317
16	Canada	29	10	326
17	Hungary	29	7	141
18	Singapore	24	7	217
19	Austria	23	7	164
20	Czech Republic	19	5	68
21	Turkey	19	6	122
22	Mexico	17	6	114
23	South Africa	17	4	44
24	Finland	16	3	33
25	Malaysia	16	4	70

The biggest cluster identified by red color consists of institutions from China, New Zealand, Italy and Germany.

5. Most productive countries

In this section, the contribution of different countries in industry 4.0 research is analyzed. Table 11 lists the 15 most productive countries along with the TC and H-index attracted by these publications. China has the highest number of publications (TC=191) followed by Germany (TC=176), Italy (TC=130), USA (TC=118) and Spain (TC=114). Out of the 15 countries in the list only two countries belong to the developing counties groups. It means that the research is industry 4.0 is still gripping in the developing countries. However, even in these young years the presence of developing countries in the list shows that it has a bright future. In terms of TC and h-index, China again tops the list with TC of 2350 and an H-index of 24. China is followed by Germany (TC=1839, h-index=20), England (TC=1077, h-index=16) and USA (TC=1035, H-index=16).

Fig. 6 shows a distribution of publications in the form of co-authorship network of countries. The size of the nodes is relative to the number of publications by each country and the edges represent collaboration. Nodes with high cohesion from a cluster. USA along with England, Brazil, India, Singapore and Taiwan form a major cluster wherein all members of the cluster have good contribution in terms of publications as can be seen by the size of nodes which is directly proportionate to the number of publications. Another major cluster includes Sweden, Germany, Italy, Austria etc. China forms center of another big cluster; however, other members of this cluster have comparatively exceedingly small contribution. China is the biggest node and has the highest link strength of 153. USA follows with a link strength of 134. Other countries in the network are England (108), Germany (108), Italy (65), Spain (58), France (56), Australia (52), India (44), and Sweden (43).

6. Keyword analysis

In this section, the keywords used in the industry 4.0 publications are analyzed. The most used keywords or the most favored research areas are shown in this study. An exhaustive list of keywords over the years is shown in Table A.1 in the Appendix. Temporal lists wherein the total period (2013–2019) is divided into three sub-periods 2013–2017, 2018 and 2019 are shown in Tables A.2–A.4, respectively, in the Appendix. The keyword "Industry 4.0" has been disregarded in this analysis; however, it is a part of the list. In the period 2013–2019 the top keywords are Internet of Things (IOT), Cyber Physical Systems (CPS), Big Data, Smart Factory, Smart Manufacturing and Industrial Internet of Things (IIOT) with occurrence counts 173, 127, 58, 56, 52 and 48. For the period 2013–2017, the top keywords are IOT, CPS,

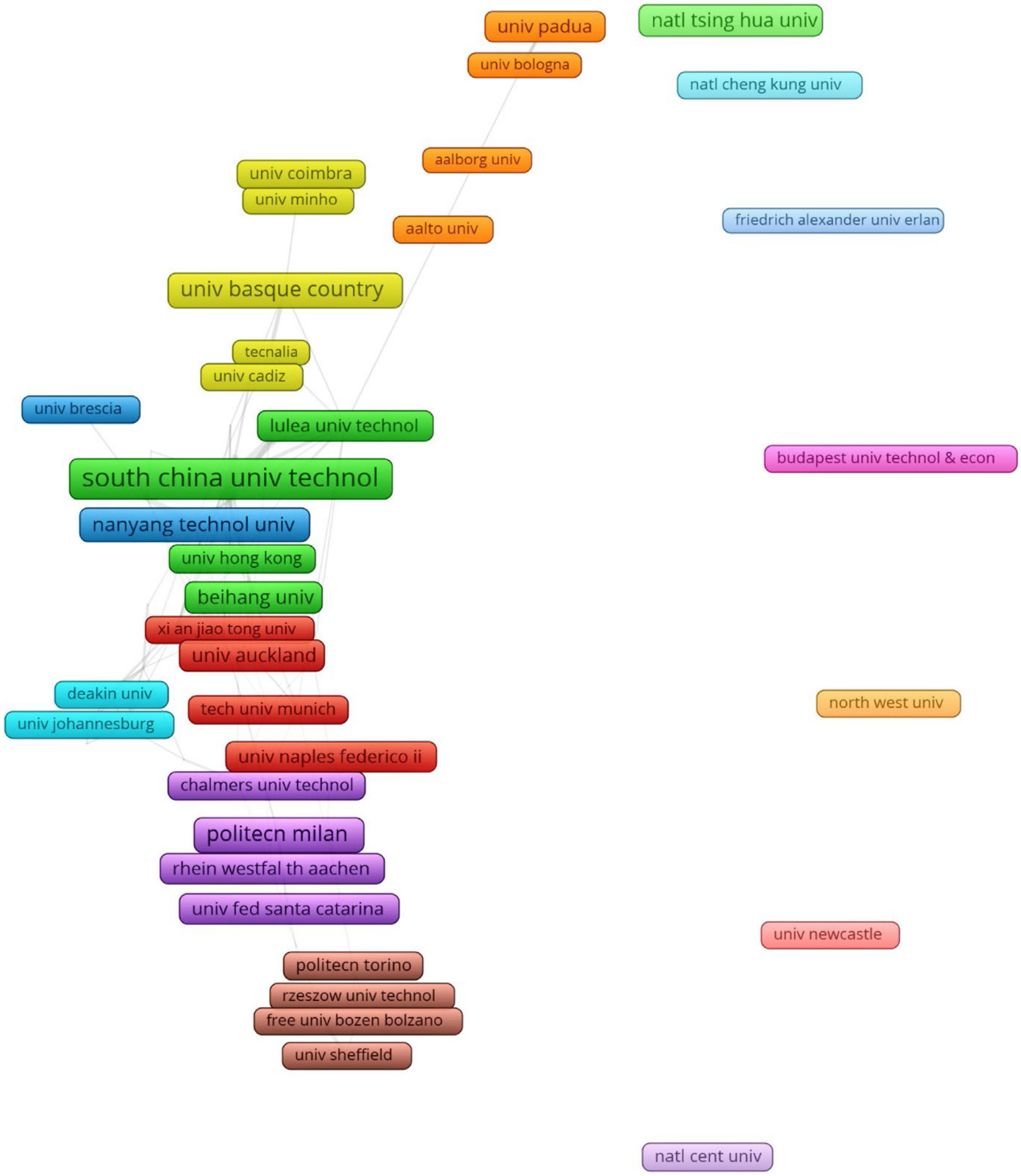

Fig. 5. Co-authorship network of institutions.

Big Data, Smart Factory and Cloud Computing with occurrence counts 28, 22, 15, 13 and 11. Since, the last two years (2018 and 2019) have been the most productive years, they are analyzed separately. The top keywords of year 2018 as shown in Table A.3 which are IOT, Smart Factory, IIOT, Big data and CPS. For the year 2019, the top keywords are shown in Table A.4 (in Appendix) and include IOT, CPS, Smart Manufacturing, IIOT and Big Data. The keywords are further analyzed to visualize their usage structure. Visualization and analysis tool Citespace have been used for this purpose. A total of 24 clusters were found when all the keywords are extracted from the data. Fig. 7 shows the top 11 clusters of these most common keywords in the publications of our contention. The clusters are marked using cluster id (#0 - #10). Further, the naming of the cluster has been done using the log-likelihood ratios. The overlapping of clusters means that the keywords are used a lot in conjunction with others.

More information about the clusters in Fig. 7 is given in Table 12. It shows the cluster id (unique identification number) given to each cluster, the number of nodes in each cluster i.e. the size of the cluster, the silhouette i.e. the similarity of a node with the nodes of its cluster versus the nodes of other clusters and mean year i.e. the average of the publication year of all member nodes. The clusters in Fig. 7 have been named using log likelihood ratios. The biggest cluster is of size 64 with the cluster name “smart manufacturing”. It has a silhouette of 0.812 and the mean year is 2016.

Further Table 13 shows the citation burst of the top six keywords. The publication year, citation burst begin and end year and the total span of the burst is also given. The keyword “RFID” had a citation burst of two years. The oldest keywords in the list are “Industrial Wireless Network” and “Cyber-physical Systems” with a burst span of three and two years, respectively. The youngest keyword is “Environment” with a burst span of two years.

7. Growth of research areas in Industry 4.0

Since its inception, Industry 4.0 has been attracting the attention of research fraternity of almost all domains. This fact can be concluded from the previous sections where we have seen growth Industry 4.0 publications. Concatenating to that, in this section, the various research areas where Industry 4.0 has been published, are discussed. Table 14 lists the top 25 research areas. The list has been sorted in the order of

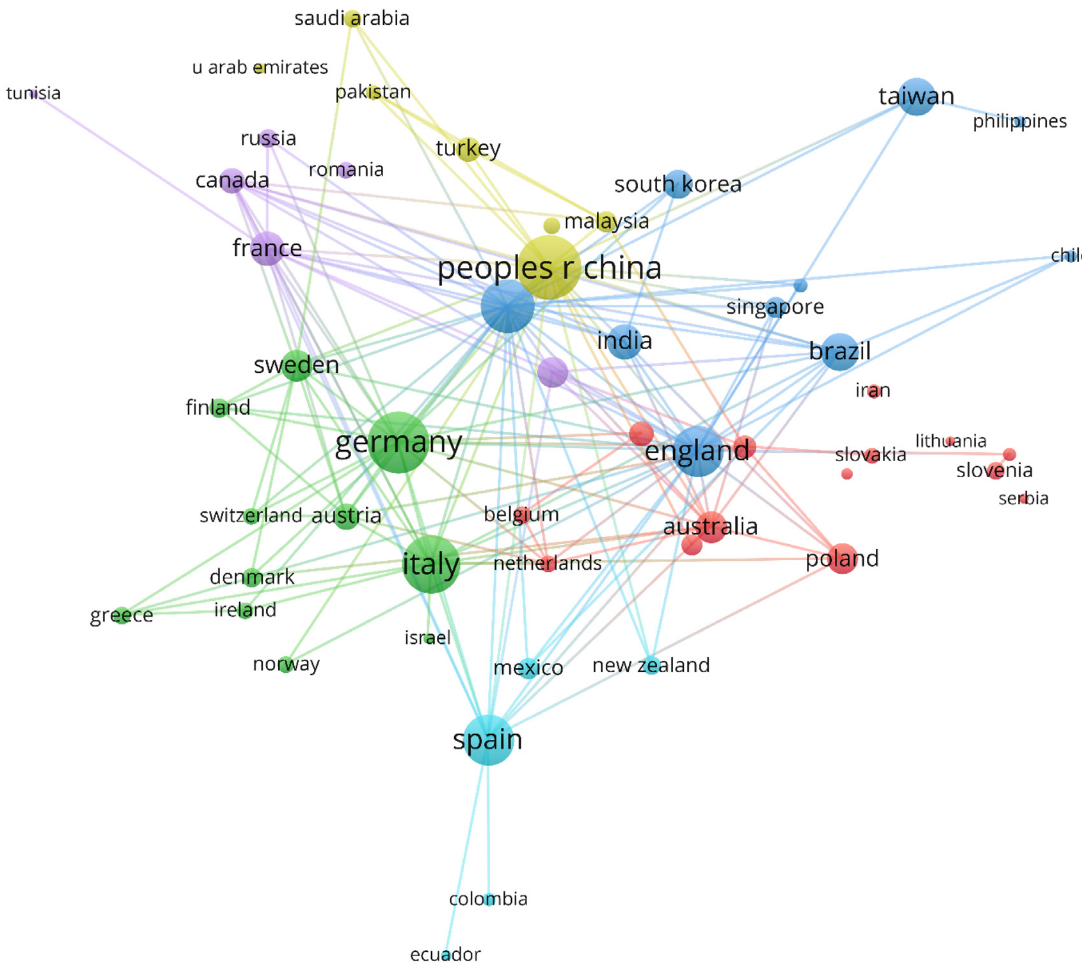

Fig. 6. Co-authorship network of Countries.

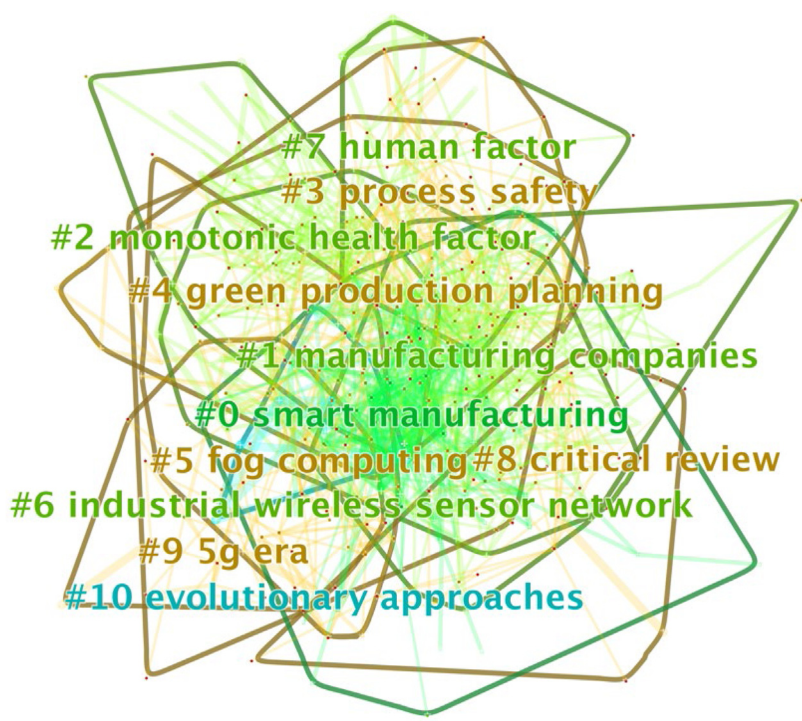

Fig. 7. Top keywords in Industry 4.0 publications.

Table 12
Cluster information of keywords.

Cluster Id	Size	Silhouette	Mean year	TFIDF	Log-likelihood	Mutual information
0	64	0.812	2016	Big data	Smart manufacturing	Leading innovation
1	62	0.665	2017	Smart manufacturing	Manufacturing companies	Complexity metrics
2	48	0.753	2017	Predictive maintenance	Monotonic health factor	Successful industry
3	37	0.704	2018	Cyber physical systems	Process safety	Lean automation interface
4	36	0.567	2018	Smart production	Green production planning	Complexity metrics
5	35	0.631	2018	Industrial augmentation	Fog computing	NPV approach
6	32	0.679	2017	Wireless sensor networks	Industrial wireless sensor networks	Cyber physical system integration
7	23	0.864	2017	Human factors	Human Factors	Long production factories
8	21	0.749	2018	Manufacturing	Critical review	Collaborative Service-component Integration
9	18	0.765	2018	Indoor visual localization	5g Era	Supply chain management studies
10	8	0.944	2015	Cloud Computing resource scheduling	Evolutionary approaches	Smart manufacturing

Table 13
Citation burst of top 6 keywords.

	Keyword	Burst	PY	Burst Begin	Burst End	Span
1	RFID	2.4471	2016	2016	2017	2
2	Resource	2.2631	2016	2016	2017	2
3	Environment	2.3493	2017	2017	2019	3
4	Industrial wireless network	2.786	2015	2015	2017	3
5	Sensor	2.4779	2016	2016	2019	4
6	Cyber-physical system	5.4964	2015	2016	2017	2

Table 14
Research areas with publications in Industry 4.0.

R	Research area	TP
1	Engineering	774
2	Computer science	424
3	Operations research management Science	143
4	Telecommunications	143
5	Automation control systems	132
6	Chemistry	90
7	Instruments instrumentation	81
8	Materials science	80
9	Science technology other topics	71
10	Environmental sciences ecology	70
11	Physics	37
12	Robotics	26
13	Food science technology	20
14	Business economics	18
15	Construction building technology	18
16	Energy fuels	18
17	Mathematics	15
18	Metallurgy metallurgical engineering	14
19	Polymer Science	13
20	Biotechnology applied microbiology	11
21	Thermodynamics	7
22	Agriculture	6
23	Education educational research	6
24	Optics	4
25	Biochemistry molecular biology	3

maximum publications. The SC option available in the WoS data has been used to prepare the list.

Engineering is the domain with most publications (TP = 774) and sits at the first position. Computer Science is second with 424 publications, followed by operations research management science (TP = 424), telecommunications (TP = 143), automation control systems (TP = 143), chemistry (TP = 90), instruments and instrumentation (TP = 81), materials science (TP = 80) and science and other topics (TP = 71). One research publication can be a part of more than one research areas as these are overlapping in nature. To access the growth of individual research area over the years, the individual contribution of the top 25 research areas is shown in Fig. 8, wherein, each research area is mapped against its publication years. It can be seen that Engineering and Computer Science have maintained top position since the inception. Telecommunications had a good start however it receded after the year 2018 and operation research management science took over. Automation control Systems, Chemistry, Instruments Instrumentation, Material Science, Science and other topics, Environmental Science Ecology and Physics are other research areas which have particularly performed well in the last two years (2018 and 2019).

8. Research themes identification using machine learning techniques

The advent of machine learning in natural language is bringing about far-reaching changes in how machines understand human language. In this section, we present an analysis of the abstracts present in the data extracted with the identifier ‘AB’. WoS attaches every record with a unique identifier called ‘UT’ and looks like ‘‘WOS: 000458929500336’’. Every publication record in the WoS database has

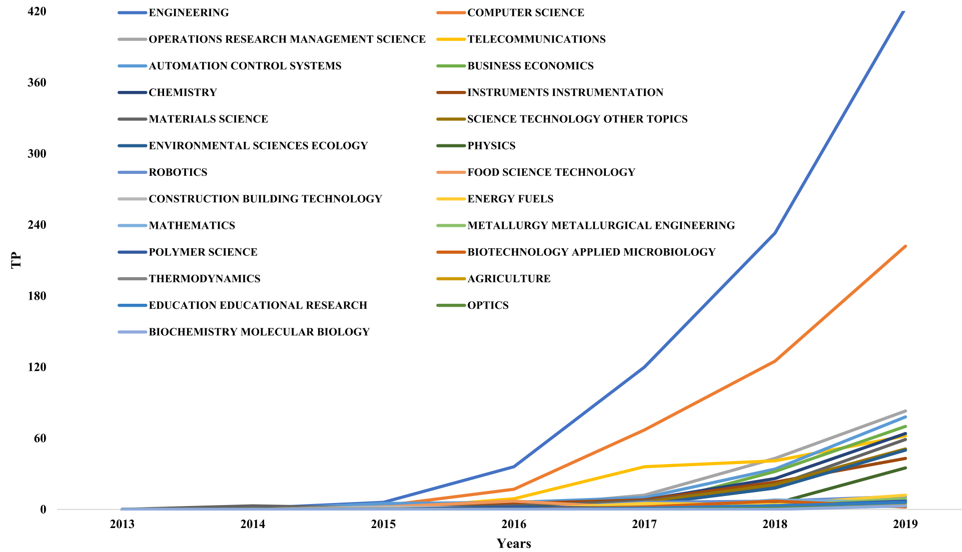

Fig. 8. Publication growth of research areas over the years.

Table 15
Size of clusters.

Cluster ID	Number of members
Cluster 0	224
Cluster 1	189
Cluster 2	122
Cluster 3	197
Cluster 4	349

its own unique identifier. The data flow is shown in Fig. 9 as a six steps process.

The first step is extraction of abstract and UID from the database. The second step is data preprocessing wherein the extracted features are subjected to tokenization, stop words filtering and stemming. It is followed by tokenization and stemming of words. Unigrams, bi-grams and tri-grams has been used for this study. In the next step, the whole corpus is transformed into vector space using term frequency–inverse document frequency. Thereafter cosine similarity between the different abstracts is calculated. K-means algorithm is used to further cluster the abstracts into 5 different clusters (number 5 has been decided empirically). For cluster visualization multidimensional clustering has been used. The number of nodes in each cluster is listed in Table 15 and the visualization of the clusters is shown in Fig. 10.

The clusters obtained are highly overlapping in nature. To further bring about the true essence of each cluster, Latent Dirichlet Allocation (LDA), a topic modeling is used on each of the clusters obtaining the most suitable words describing the cluster. The cluster and their corresponding terms are listed in Table 16. Cluster 0 and cluster 1 mainly seems overlapping as they both give a hint of industry and manufacturing. However, Cluster 1 contains the real essence of Industry 4.0 with the presence of keywords such as smart, digital, data etc. Cluster 2 gives an essence of IOT based applications. Cluster 3 includes study the performance analysis and modeling. Cluster 4 shows us that a lot of publication in the domain of Industry 4.0 are review papers and thus, we have keywords such as review, literation, research etc. It also includes the domain of healthcare in Industry 4.0.

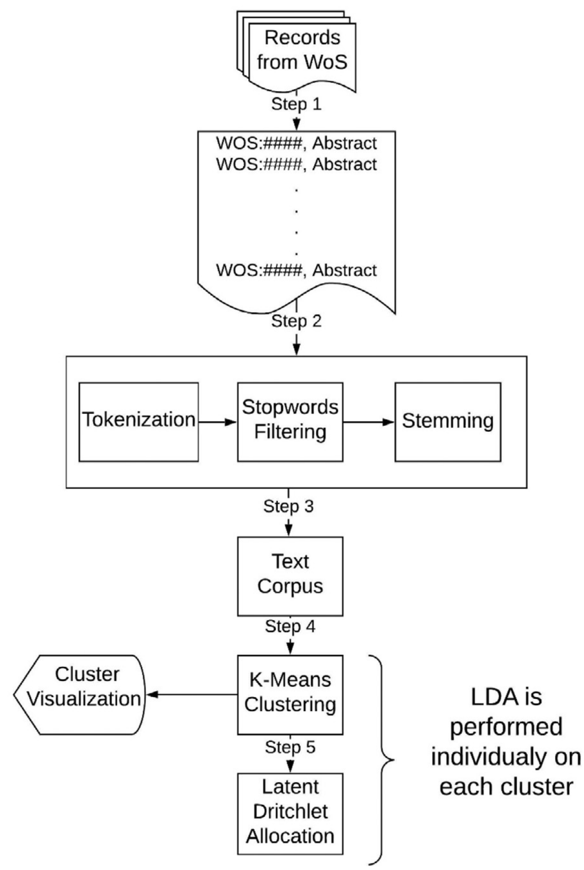

Fig. 9. Data flow Diagram.

9. Discussion and conclusion

In this paper, we have explored the scientometric landscape of Industry 4.0 publications along with research theme identification within the Industry 4.0 purview. This study first establishes the pillars of the Industry 4.0 viz. IoTs, Big data, system integration, cloud computing, additive manufacturing, augmented reality, simulation, robotics, AI, and cyber security. Then, the publication and citation structures of Industry 4.0 papers (in WoS) are explored. It was found that the first publication came in the year 2013. The year 2019 was the most productive year with 594 publications (48% of the total publications). However, the year 2018 has the most influential publications attracting a total of 2780 citations. The top cited paper of each year (2013–2020) has also been visited. The year 2014 has the most CPP attracting

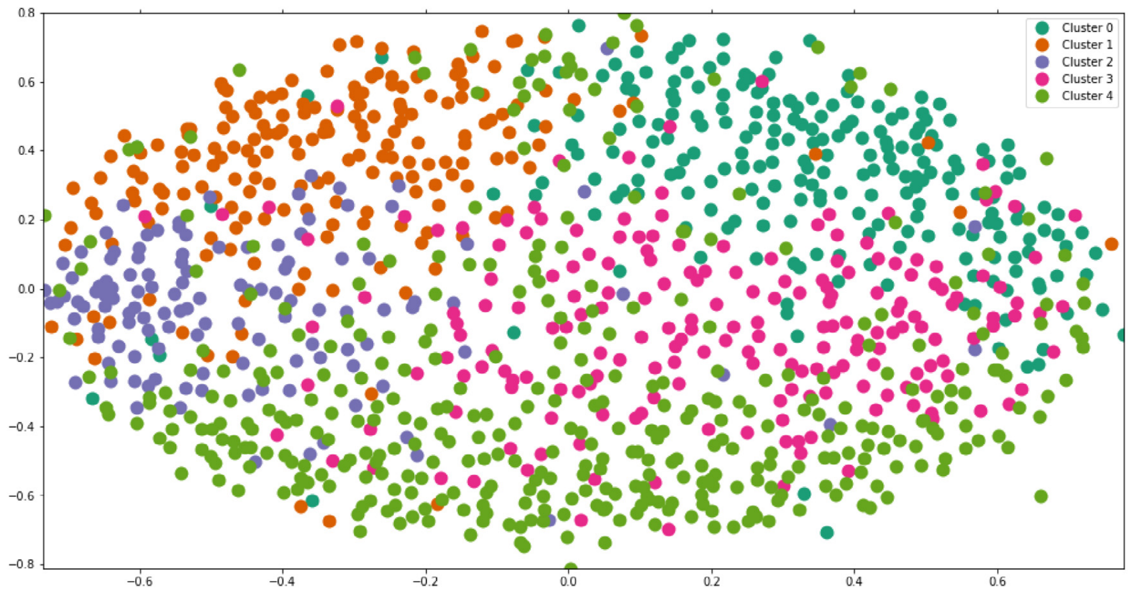

Fig. 10. K-means clusters of abstracts.

Table 16
LDA terms for k-means clusters.

Cluster ID	LDA terms
Cluster 0	Production, process, design, assembly, manufacturing, time, learning, model, product, method
Cluster 1	Industrial, smart, data, industry, information, digital, challenges, production, paper, technologies
Cluster 2	Data, sensor, devices, communication, network, cloud, control, computing, performance, smart, applications
Cluster 3	Model, data, chain, environmental, analysis, performance, waste, green, monitoring, circular
Cluster 4	Healthcare, scientific, literature, scheduling, maintenance, review, studies, logistics, review, research

499 citations from 5 papers. However, the years 2017 and 2018 have the highest h-index of 25 each. Two papers received more than 200 citations, while 38% remains uncited. The top 50 cited and most referenced papers are also visited. The paper titled "Industry 4.0" by Lasi et al. published in the year 2014 has the highest citation of 465. The most referenced by Lee et al. has been referenced 170 times by Industry 4.0 publications. The paper is titled "A cyber-physical systems architecture for industry 4.0-based manufacturing systems" and was published in the year 2015. IEEE Access is the most favored journal with a total of 73 publications.

Authorship in Industry 4.0 publications is also explored, highlighting highly productive and influential authors. Li D is the most productive author with maximum collaborations. Co-authorship network of authors is visualized identifying important group of authors collaborating with each other. South China University of Technology of China is the most productive, influential and collaborative institution. The top keywords in Industry 4.0 publications are Big Data and Smart Manufacturing. Engineering is the research areas which has shown the highest individual growth in Industry 4.0. To identify various research themes, K-means clustering and LDA has been used over the abstracts. Empirically five different clusters were identified using k-means which are further subjected to LDA for topic modeling.

In general, this paper provides an overall outline of the Industry 4.0 publications till date published in WoS. Industry 4.0 has come a long way and is showing promising growth as a research area. This growth in research comes in hand with promising adoption of Industry 4.0 tools and technologies by modern industry. The advancements brought in by Industry 4.0 has largely impacted the lives of humans which in turn has led to another paradigm called the Society 5.0, wherein, the tool and technologies of Industry 4.0 are used to improve the quality of life of the society. The evolution of this new domain gives us an opportunity to explore the scale of evolution of Industry 4.0 in near future.

With respect to the extension of this work, we shall work with the fuzzy clustering of the research themes and other entities for the multi-disciplinary research analysis.

CRediT authorship contribution statement

Manvendra Janmaijaya: Data curation, Methodology, Visualization, Formal analysis, Writing - original draft, Writing - reviewing. **Amit K. Shukla:** Conceptualization, Validation, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **Pranab K. Muhuri:** Conceptualization, Validation, Supervision, Writing - review & editing, Project administration. **Ajith Abraham:** Conceptualization, Validation, Writing - review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

See Tables A.1–A.4.

Table A.1
Top keywords in Industry 4.0 Publications over the years.

Rank	Keyword	Occurrences	Rank	Keyword	Occurrences
1	Internet of Things	173	51	Industrial wireless networks	8
2	Cyber physical system	127	52	Interoperability	8
3	Big data	58	53	Literature review	8
4	Smart factory	56	54	robotics	8
5	Smart manufacturing	52	55	Sustainable manufacturing	8
6	Industrial Internet of Things	48	56	Assembly	7
7	Cloud computing	42	57	Genetic algorithm	7
8	Machine learning	26	58	Information technology	7
9	Sustainability	25	59	Innovation	7
10	Additive manufacturing	23	60	Maintenance	7
11	Blockchain	18	61	Semiconductor manufacturing	7
12	Digital twin	18	62	Sensors	7
13	Digitalization	18	63	Survey	7
14	Artificial intelligence	17	64	Advanced manufacturing	6
15	Cloud manufacturing	17	65	Digital factory	6
16	Manufacturing	17	66	Engineering education	6
17	Security	17	67	Fault diagnosis	6
18	Augmented reality	16	68	Flexible manufacturing	6
19	Intelligent manufacturing	16	69	Fourth industrial revolution	6
20	Simulation	16	70	Human factors	6
21	Supply chain management	16	71	Industrial big data	6
22	Circular economy	15	72	Lean manufacturing	6
23	Automation	14	73	Logistics	6
24	Deep learning	14	74	Machining	6
25	Digital transformation	14	75	Multi-agent system	6
26	Digital manufacturing	13	76	Multi-agent systems	6
27	Fog computing	13	77	Production planning	6
28	Ontology	13	78	Reliability	6
29	Scheduling	13	79	scada	6
30	Digitization	12	80	Small and medium-sized enterprises	6
31	opc ua	12	81	Smart manufacturing systems	6
32	Wireless sensor network	12	82	Sustainable development	6
33	Industrial internet	11	83	Traceability	6
34	Supply chain	11	84	Business model	5
35	Virtual reality	11	85	Case studies	5
36	3D printing	10	86	Computer architecture	5
37	Cybersecurity	10	87	Computer vision	5
38	Predictive maintenance	10	88	Control	5
39	RFID	10	89	Cyber-physical production system	5
40	Smart grid	10	90	Data analysis	5
41	Big data analytics	9	91	Decision making	5
42	Cyber-physical production systems	9	92	Decisional dna	5
43	Edge computing	9	93	Design	5
44	Manufacturing systems	9	94	Factories of the future	5
45	Optimization	9	95	Flexibility	5
46	Systematic literature review	9	96	Framework	5
47	5G	8	97	Industrial wireless sensor networks	5
48	Condition monitoring	8	98	Integration	5
49	Discrete event simulation	8	99	Latency	5
50	Energy efficiency	8	100	Lean production	5

Table A.2
Top keywords in Industry 4.0 Publications from 2013–2017.

Rank	Keyword	Occurrences	Rank	Keyword	Occurrences
1	Industry 4.0	121	26	Reliability	2
2	Internet of Things	28	27	Smart grid	2
3	Cyber-physical systems	22	28	Wirelesshart	2
4	Big data	15	29	Centralized tdma	1
5	Smart factory	13	30	Distributed energy systems	1
6	Cloud computing	11	31	Energy consumption	1
7	Cyber-physical system	9	32	Energy distribution	1
8	Industrial wireless networks	6	33	Energy management	1
9	Intelligent manufacturing	6	34	Energy storage	1
10	Smart manufacturing	6	35	Field test	1
11	rfid	5	36	Latency	1
12	Automation	4	37	Link scheduling	1
13	Cyber physical system	4	38	Load balancing	1
14	Digital factory	4	39	Load shifting	1
15	Factories of the future	4	40	Localization	1
16	Manufacturing systems	4	41	Multi-antenna techniques	1
17	Design	3	42	Multi-hop wireless networks	1

(*continued on next page*)

Table A.2 (*continued*).

Rank	Keyword	Occurrences	Rank	Keyword	Occurrences
18	Industrial wireless sensor networks	3	43	Renewable energy generation	1
19	Manufacturing	3	44	rss	1
20	Scheduling	3	45	scada	1
21	Security	3	46	Shared links	1
22	Systematic literature review	3	47	Shipyard 4.0	1
23	Industrial wireless communications	2	48	Smart home	1
24	isa100.11a	2	49	Smart metering	1
25	Performance	2	50	Smart pipes	1

Table A.3
Top keywords in Industry 4.0 publications in the year 2018.

Rank	Keyword	Occurrence	Rank	Keyword	Occurrence
1	Industry 4.0	218	26	Manufacturing	5
2	Internet of Things	65	27	opc ua	5
3	Smart factory	23	28	Semiconductor manufacturing	5
4	Industrial Internet of Things (iiot)	23	29	Simulation	5
5	Big data	19	30	3D printing	4
6	Cyber-physical systems	17	31	Big data analytics	4
7	Cloud computing	14	32	Digital manufacturing	4
8	Smart manufacturing	14	33	Digital transformation	4
9	Industrial internet of things	11	34	Digitalization	4
10	Sustainability	10	35	Edge computing	4
11	Additive manufacturing	9	36	Industrial internet	4
12	Cyber-physical system	8	37	Innovation	4
13	Fog computing	7	38	Interoperability	4
14	Augmented reality	6	39	Literature review	4
15	Cloud manufacturing	6	40	Process safety	4
16	Deep learning	6	41	Computer architecture	3
17	Machine learning	6	42	Cyber-physical systems (cps)	3
18	Ontology	6	43	Industrial augmented reality	3
19	Security	6	44	Industrial iot	3
20	Smart grid	6	45	Job safety	3
21	Supply chain management	6	46	rfid	3
22	Artificial intelligence	5	47	Scheduling	3
23	Blockchain	5	48	Sensors	3
24	Fourth industrial revolution	5	49	Smes	3
25	Intelligent manufacturing	5	50	Tracking	3

Table A.4
Top keywords in Industry 4.0 publications in the year 2019.

Rank	Keyword	Occurrences	Rank	Keyword	Occurrences
1	Industry 4.0	463	26	Scheduling	9
2	Internet of Things (iot)	80	27	Supply chain	9
3	Cyber-physical system	50	28	Digital manufacturing	8
4	Smart manufacturing	34	29	Security	8
5	Industrial Internet of Things	28	30	Technology	8
6	Big data	24	31	3D printing	7
7	Digitalization	22	32	Automation	7
8	Smart factory	22	33	Cloud manufacturing	7
9	Cloud computing	18	34	Condition monitoring	7
10	Additive manufacturing	17	35	Cybersecurity	7
11	Machine learning	17	36	Systematic literature review	7
12	Artificial intelligence	15	37	5g	6
13	Blockchain	15	38	Big data analytics	6
14	Sustainability	15	39	Cyber-physical production systems	6
15	Digital transformation	13	40	Edge computing	6
16	Digital twin	13	41	Fog computing	6
17	Digitization	12	42	Framework	6
18	Supply chain management	12	43	Literature review	6
19	Augmented reality	11	44	opc ua	6
20	Circular economy	11	45	Robotics	6
21	Manufacturing	11	46	Smes	6
22	Deep learning	10	47	Interoperability	5
23	Simulation	10	48	Optimization	5
24	Virtual reality	10	49	Predictive maintenance	5
25	Innovation	9	50	Latency	4

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